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MARTIN MARIETTA

**COOLING TOWER DRIFT STUDIES
AT ORGDP - FINAL REPORT**

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INTRODUCTION

During the 1970s, a major consideration in environmental impact studies of electric power plant operations was the effects of cooling tower drift. In 1973 the distribution and magnitude of drift from mechanical draft cooling towers at the Oak Ridge Gaseous Diffusion Plant (ORGDP), Oak Ridge, Tennessee, was investigated (Taylor et al., 1975). That study provided evidence of the transport and deposition of drift to the terrestrial environment, but only depicted a single season from over three decades of continuous operation. Results of that study suggested that increased quantities of trace elements (chromium) in vegetation attained an equilibrium concentration with environmental losses (weathering, leaching) compensated by chronic deposition.

The cooling towers investigated in the 1973 study were built in the early 1950s, but were constantly remodeled and upgraded over this time period. However, 0.03% to 0.1% drift percentage obtained in the 1973 study (Jallouk et al., 1974) was considerably higher than some of similar towers constructed later as shown in Table 1. The ORGDP diffusion process production rate is varied by changing the operating power level of the plant which, in turn, is related to the recirculating cooling water (RCW) flow rate. Drift fraction is a function of the RCW flow, such that variations (seasonal) in plant operation influence drift emissions. Beginning in 1978 a series of studies were initiated to resolve several issues. A short-term study was designed to assess the high drift rate identified in the 1973 study as well as to collect sufficient deposition data to validate a drift dispersion model. The short-term study was conducted with simultaneous measurements of the source and deposition to formulate the source characteristics and deposition pattern. The long-term study was conducted to test the hypothesis that a change in the level of plant operations could be detected in seasonal vegetation analysis (biomonitoring), and to determine if any anomalous conclusions were inherent in previously published assessments of drift effect (Taylor et al., 1983).

METHODS

An intensive cooling tower drift study conducted in 1978 consisted of measuring the source characteristics and deposition simultaneously for 10 days. The source characteristics were measured (3-cells from the K-31 tower and 3 1/2 cells from the K-33 tower) to determine the drift rate and its size spectrum of droplets. These measurements would define the drift rate more quantitatively than the 1973 study, where the drift rate was determined on a single cell measurement from each tower. A typical cell was selected (K-33, Cell No.1) from this study and was investigated again in the following years for evidence of yearly variations in drift emission. Besides the 10 days of concentrated deposition measurements in 1978, seasonal deposition measurements were

Table 1. Comparison of tower characteristics

	ORGDP ^a K-31-6	Turkey ^b Point	New Jersey ^c
Water flow rate, g/s	1.28×10^5	11.20×10^5	0.47×10^5
Air flow rate, cfm	6.25×10^5	9.97×10^5	0.70×10^5
L/G	0.67	1.12	1.17
Average air velocity, m/s	8	11.2	4.4
Manufacturer	Marley	Marley	Baltimore Air
Type	Cross flow (induced)	Cross flow (induced)	Cross flow (forced)
Year constructed	1951	1974	1970
Drift rate, D, g/s	36-150	3.979	0.0466-2.3
Drift percentage, Δ , %	0.028-0.1	0.00034	0.000006-0.003
Median drop size, d, μm	175-1000	125	500

^aRefer. 3, p. 29.

^bG. O. Schrecker and C. D. Henderson, Salt Water Condenser Cooling: Measurements of Salt Water Drift from a Mechanical-Draft Wet Cooling Tower and Spray Modules, and Operating Experience with Cooling Tower Materials, Proc. of Am. Power Conference, vol. 38, 1976.

^cR. O. Webb, D. A. Rutherford, and D. W. Cooke, Source and Downwind Cooling Tower Drift Data Acquired at the HUD Jersey City Total Energy Plant, prepared for Energy Division, Union Carbide Corporation, Oak Ridge National Laboratory, October 1977.

conducted in 1979, 1980, and 1981. The summary of the sampling schedule is shown in Table 2.

The source characteristics of each cooling tower was measured with water sensitive papers for droplet diameter spectrum and an isokinetic tube for the mineral flux. The sensitive papers were exposed in the plume for a duration of a few seconds to several minutes depending on the sampling position in the fanstack compared to 30 min to an hour for an isokinetic tube. Hence, the mineral fluxes measured with an isokinetic tube were better time averaged values with more than 90% efficiency of capturing all sizes of droplets (Shofner et al., 1974). The sensitive papers, however, measured the spectrum of droplets in the

Table 2. Summary of source and deposition measurements

<u>Year</u>	<u>Source measurement</u>	<u>Deposition measurement</u>
1978	By ESC ^a 3 cells from K-31 3 1/2 cells from K-33	For 10 days (Aug and Sept)
1979	By SEA ^b K-33, cell 1	Seasonal measurement July and October
1980	By ORGDP ^c K-33, cell 1	May and August
1981	None	June and July

^aEnvironmental Science Corporation, Knoxville, Tenn.

^bShofner Engineering Associates, Knoxville, Tenn.

^cDepositions were measured by the ORGDP and Oak Ridge National Laboratory (ORNL) personnel.

plume with a short exposure which negatively influenced the estimate of drift rate, because it underestimates the number of large droplets, which occurs infrequently but constitute the major fraction to volume. Hence, the drift rate obtained by the isokinetic method would be higher and more representative, than that obtained by the sensitive paper method.

The drift deposition measurements were conducted in the northeast sector from the cooling towers. The prevailing wind at the ORGDP was from southwest to northeast and this area was also free from any large obstacles to interfere with the measurements. The measurements were conducted along three azimuths from the center of the cooling tower with an angular spacing of 11.25 degrees as shown in Figure 1. The sampling positions along an azimuth were approximately 50, 100, 250, 500, 750, and 1,000 m from the cooling tower. On a given day, any three consecutive azimuths were chosen such that the middle azimuth coincided with the predominant wind direction of the day. At each sample station, an 20 x 25 cm sensitive paper and an 20 cm diameter dish with 10 mL of double-distilled water were used to measure droplet count and mineral deposition, respectively. The water was added to the dish to enhance removal of the intercepted mineral.

Live foliage and litter of fescue grass (*Festuca arundinacea* Schreb) were collected from permanent sampling stations along five radial transects from the K-892 cooling tower. Samples were collected following a change in corresponding change in the RCW flow rate. Sample periods reflected the seasons [December (Winter), April (Spring), June

(Summer), and October (Fall)]. Sample stations were located from 50 to 1600 m, as shown in Figure 2, from the cooling tower in the direction of predominant winds. Plant materials were collected from triplicate 0.03 m² plots at each location. The plot locations were the same as used in the initial cooling tower drift study of 1973 (Taylor et al., 1975). Prepared solutions of the samples were analyzed for total chromium by atomic spectrophotometry using a Perkin-Elmer Model 403 Spectrophotometer.

RESULTS

SOURCE CHARACTERISTICS MEASUREMENT

The source characteristics of number of cells from the K-31 and K-33 cooling towers measured in the 1978 study are shown in Table 3.

Table 3. Source characteristics measurement--1978 study

Tower	No. of fan measured	Drift Percentage, %		Deviation, %
		By sensitive paper	By isokinetics tube	
K-31	3	0.019	0.028	32
K-33	6	0.018	0.032	18
Total	9	0.0184	0.0237	22

The average drift percentage of the cooling towers was 0.024%. This is higher than rates reported from some of newer towers of similar design but is much lower than 0.03% to 0.1% measured in the 1973 study. The higher drift rate measured in 1973 might have been attributed to a small sampling volume of the optical system used in the study. The drift rate measured by an isokinetic tube was higher than that by sensitive papers by roughly 22% which seems to be in agreement with the assumption. The source characteristics of a typical cell, cell No.1 of the K-33 tower selected from the 1978 study, was measured again in 1979 and is compared in Table 4. The drift percentage obtained in 1979 was well within a standard deviation of the 1978 result, and, hence, assumed to be in good agreement indicating that there was no appreciable changes in drift from the tower in a year. Figure 3 shows a typical spectrum of droplets in the plume measured from one of the cooling towers. The droplets were measured and counted with an image analyzer-computer system, (Quantimet 720), using 47 mm diameter sensitive papers for droplets less than 200 μ m in diameter and 293 mm diameter sensitive papers for droplets larger than 200 μ m. The drift flux curve peaks in the 100 and 300 μ m diameter droplet sizes. The contribution of small droplets to

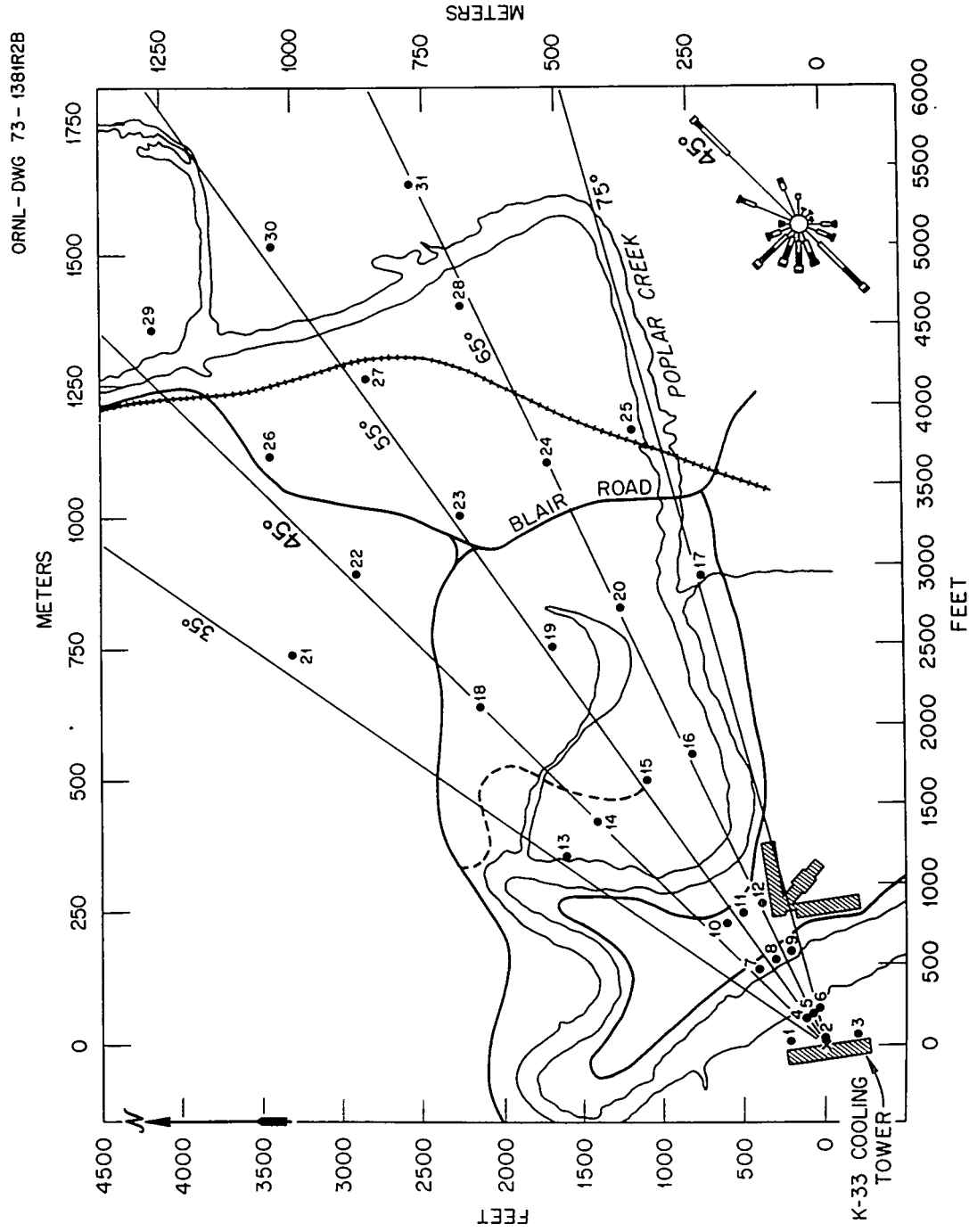


Figure 2

LOCATION OF HARVEST PLOTS NORTHEAST OF THE K-33 COOLING TOWER. THE INSERT IS WINTER WINDROSE ILLUSTRATING THE PREDOMINANT WIND DIRECTIONS, NORTHEAST AND SOUTHWEST

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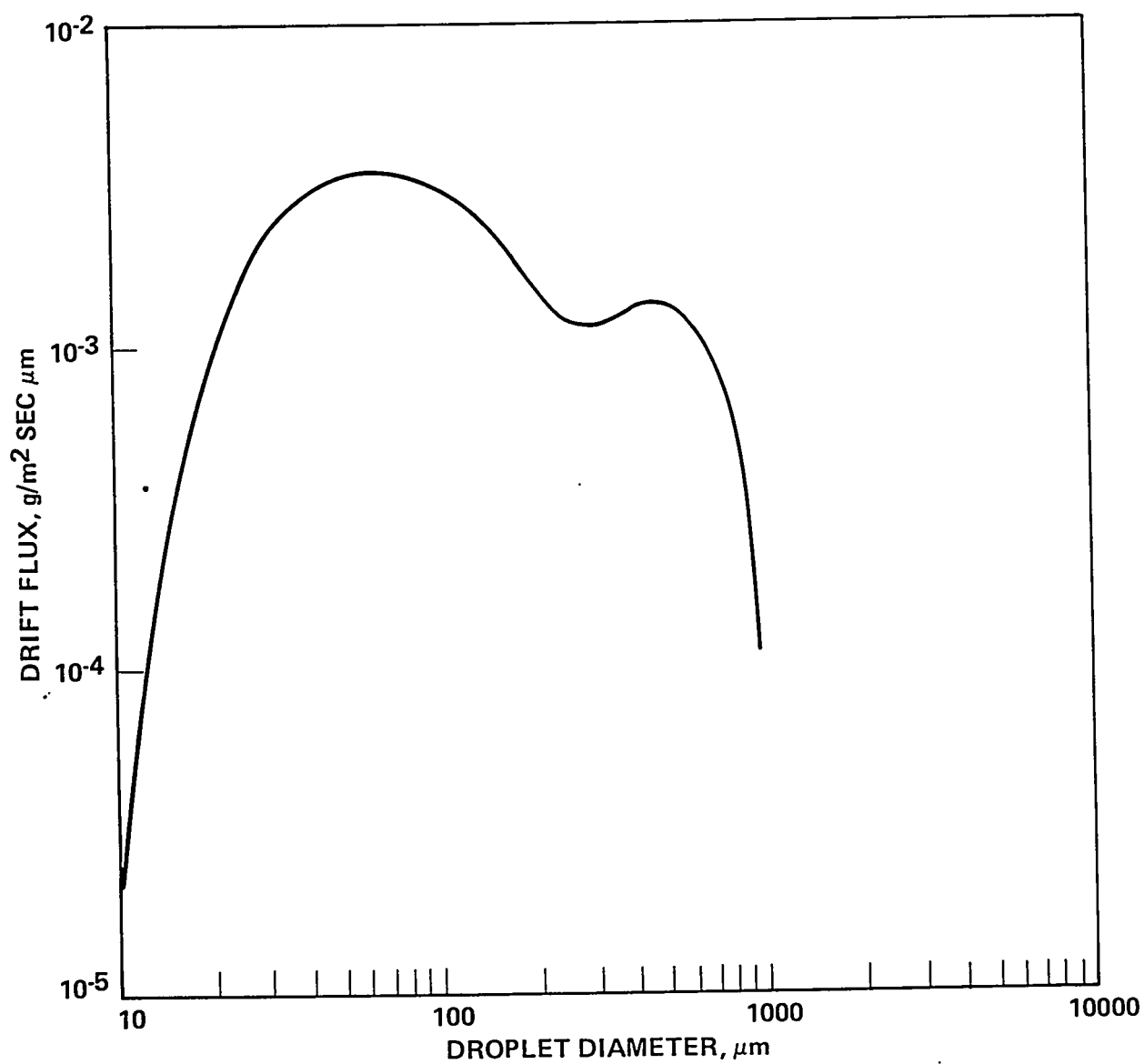


Figure 3
SPECTRUM OF DRIFT FLUX

the flux consisted of a large number of small droplets. The number of droplets counted in this area promote statistical reliability of drift in this size range. However, the drift flux of large droplet ranges are due to small number of large droplets which occur occasionally but contributes significantly to the total drift flux measurement.

Table 4. Comparison of source measurement

<u>Date</u>	<u>Drift Percentage, %</u>	<u>Standard Deviation</u>
1978	0.0237	0.009
1979*	0.0210	0.001

*1979 result is an average value of July and September measurements on K-33, Cell No. 1.

DEPOSITION MEASUREMENT

Short Term Study

The droplets and chromium depositions were measured along three adjacent azimuths in the predominant wind direction. Figures 4 and 5 show typical chromium disposition patterns with the distance from the cooling tower. The chromium deposition fluxes measured by both sensitive paper and dish methods agreed well up to 500 m from the tower (Fig. 4) before the two curves started to deviate. This suggests that the chromium deposition in the near field is in the form of droplets whereas it is in the form of mineral flakes in the far field after evaporation of droplets. The deviation point between the two measurements depended on the wind strength of the day. Hence, the influence of the wind on the chromium deposition is more sensitive to the far field than the near field where the chromium deposition depended on the trajectory of droplets.

The seasonal variations of the chromium deposition measurements are summarized in Fig. 6 where average seasonal deposition fluxes were plotted against the distance from the cooling tower. The summer and fall measurements were similar in slope while the spring measurement was lower. This might be due to the fact that the frequency of wind directional changes in the spring was higher than during the other seasons. In general, the variation of the chromium deposition flux was inversely proportional to the square of the distance from the cooling tower.

The chromium deposition measured along the three azimuths are plotted in Fig. 7. If the predominant wind direction is along the

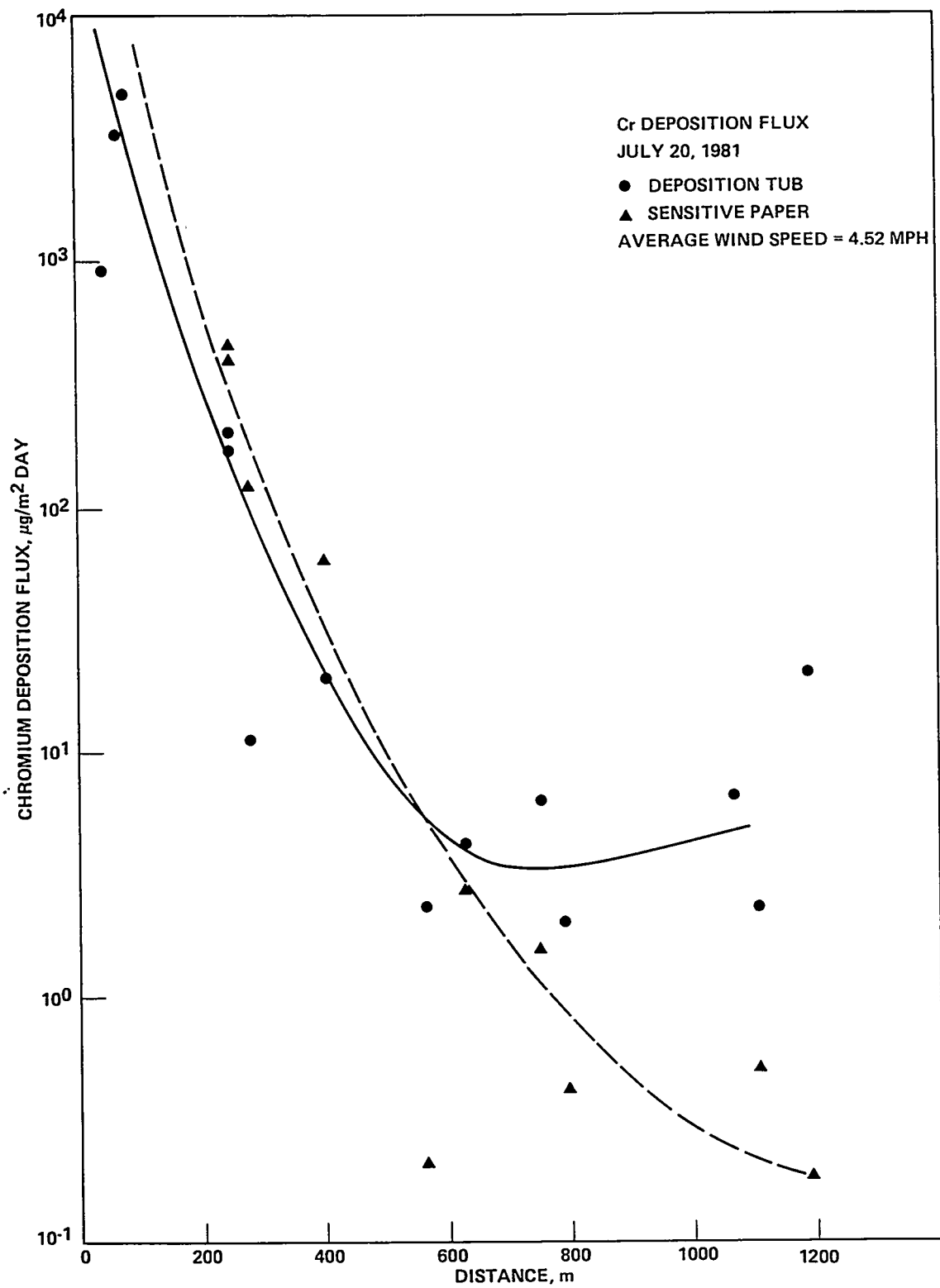


Figure 4
CHROMIUM DEPOSITION MEASUREMENT

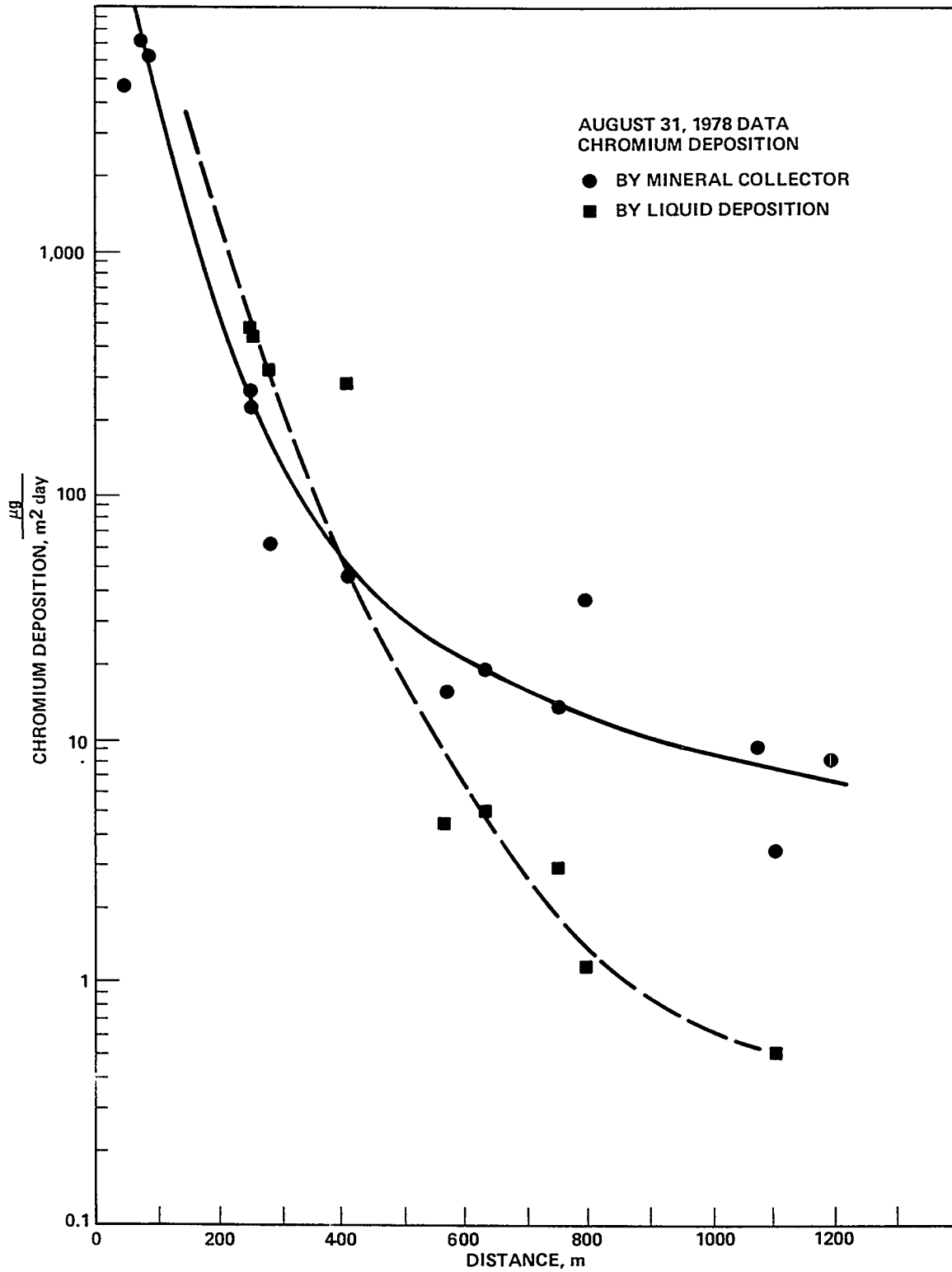


Figure 5
CHROMIUM DEPOSITION FLUX VARIATION WITH THE DISTANCE FROM
THE COOLING TOWER TEST DATA 8/31/78

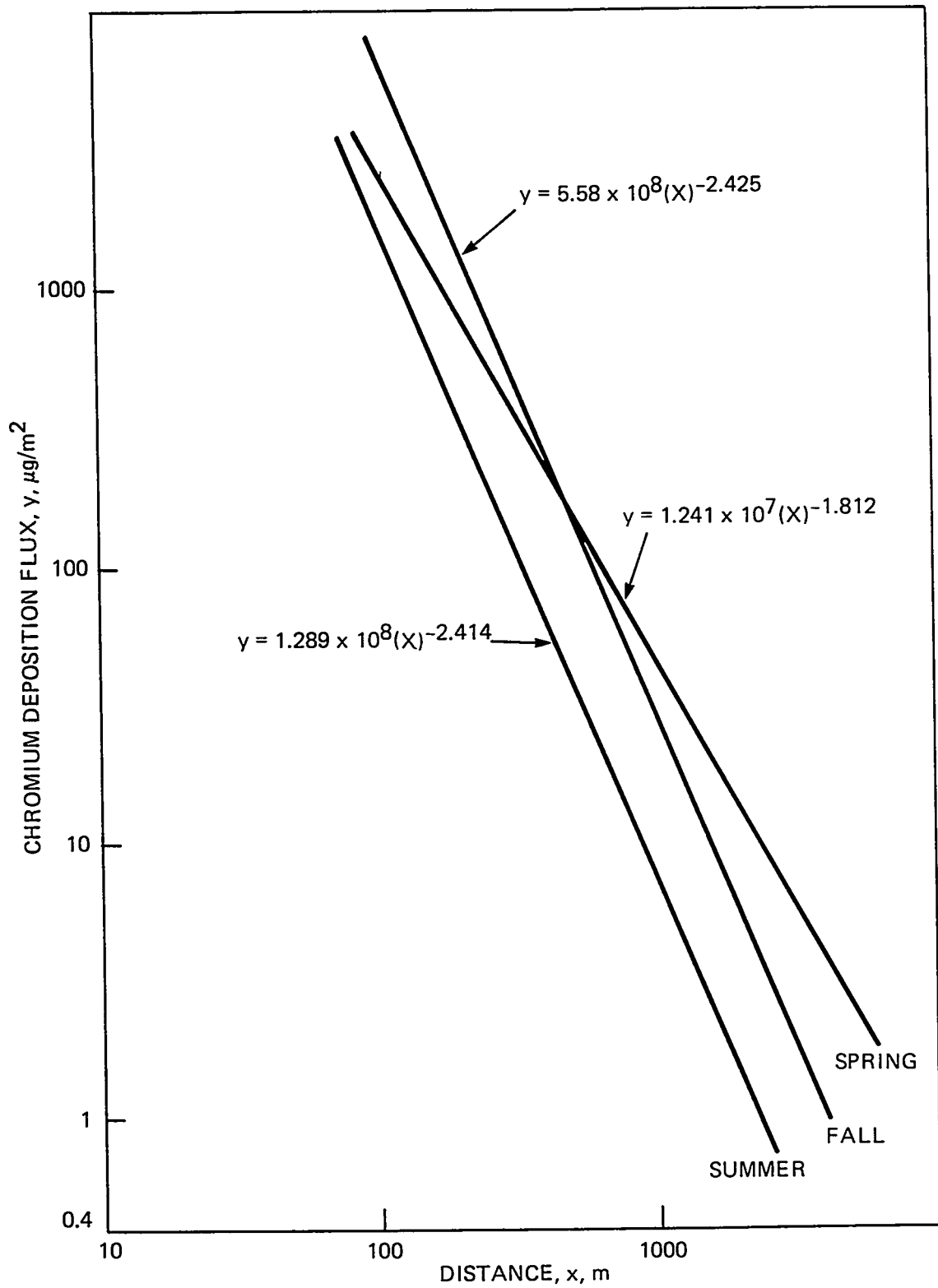


Figure 6

CHROMIUM DEPOSITION FLUX VARIATION WITH DISTANCE FROM THE
SOURCE, AND ITS SEASONAL VARIATION

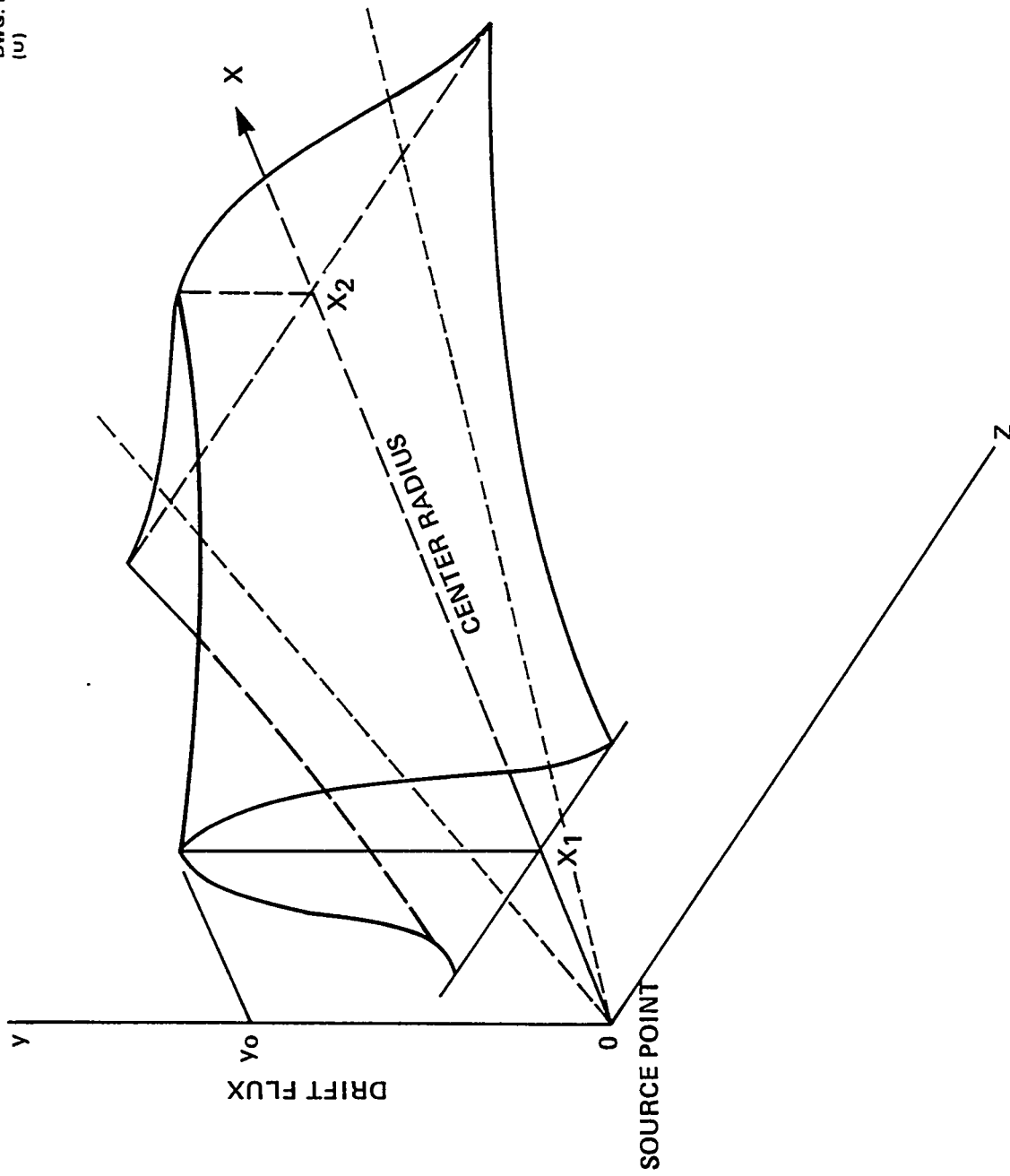


Figure 7
SCHEMATIC OF CHROMIUM DEPOSITION MODEL

x-axis, the deposition measured along the other two azimuths would be lower than that in the middle. The distribution curve at a distance x, then, may be expressed with a Gaussian distribution curve, such as

$$Y(x,z) = Y_0(x) * e^{-\eta^2 z^2} \quad (1)$$

where Y and η , disposition flux and an index of precision, respectively, were obtained from the data. Since the height of this curve, Y, represents the deposition flux, the volume under the envelope generated by this function represents the total deposition rate. The deposition data collected were analyzed and total deposition rates estimated from two radial sectors from between 50 to 1000 m from the cooling tower, resulting in a deposition area of approximately 40 ha.

Table 5. Deposition rate calculated between 50 and 1000 m from the cooling tower

Average Wind Speed, m/s	Deposition Rate g/day	Fraction of Source* %
2.23	16.68	26
3.58	11.97	19
2.93	21.65	34
3.08	12.88	21
1.34	24.39	39
9.39	33.43	53
1.13	15.62	25
0.74	49.12	78
2.02	17.18	27

*Fraction was calculated with 62.8 g/day chromium flux from a cooling tower cell based on 6,000 gal/min RCW with 8 ppm of chromium.

The deposition data measured at less than 50 m from the cooling tower were due to an occasional downwash of the plume, which did not fit into the true trajectory pattern with real time averaged value. The 1000 m upper limit was chosen because this was the farthest sampling point from the cooling tower. The results were plotted against the average wind speed of the test day as shown in Fig. 8. The total deposition rate, D, may be expressed as

$$D = c*(V)^{-0.85} \quad (2)$$

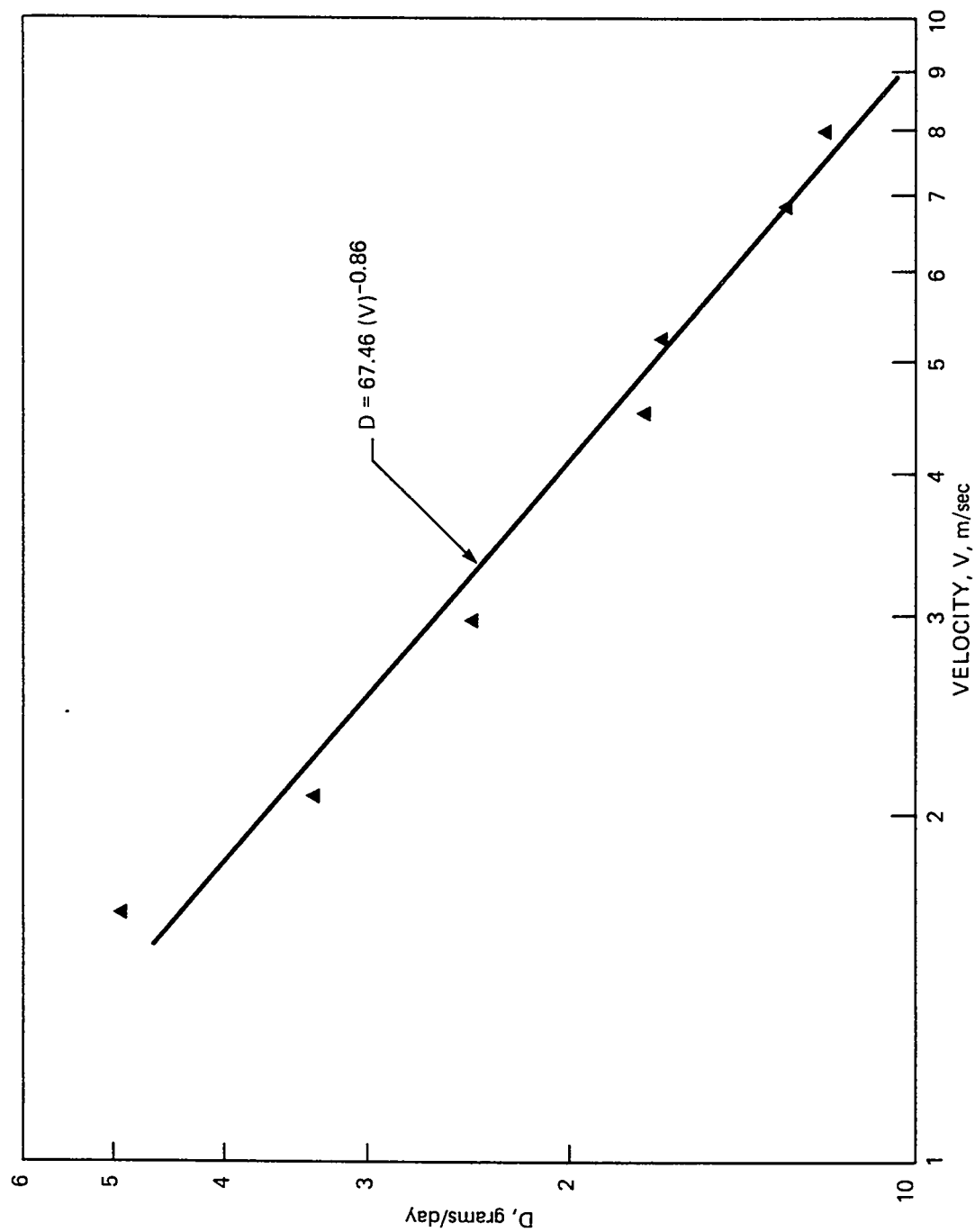


Figure 8
VARIATION OF CHROMIUM DEPOSITION RATE WITH WIND SPEED

where V is an average wind speed and c is a constant.

Long Term Seasonal Study

Data from a earlier drift study (1973) of the K-892 cooling tower indicated that foliage reached maximum chromium concentrations in 5 to 6 weeks and attained an equilibrium concentration with environmental losses (weathering, leaching) compensated by chronic deposition. As the operational level of the tower decreased a corresponding reduction in foliage concentration was observed. That suggested that chromium concentrations in vegetation may vary with seasonal plant operation (Taylor et al., 1975). To determine if vegetation contamination varied with the level of plant operation, foliage and litter were collected from permanent plots along a distance gradient from the cooling tower (Fig. 2), consisting of five radial transects. Each transect was separated 10° from adjacent transects. The mean concentrations are summarized in Table 6 as a function of season and distance from the source. With exception of samples collected at 13 and 65 m during the winter, chromium concentrations in litter generally exceeds that of foliage. In a laboratory study, throughfall from simulated rain removed three times more chromium residue from live foliage than from litter with each simulated event (Taylor et al., 1980). Drift deposited on foliage as hexavalent chromium should remain relatively water soluble, whereas deposition on litter would likely be reduced to the less soluble trivalent species by humic substances. The differences in concentration between foliage and litter is likely related to a differential solubility of chromium in the two oxidation states (Cr^{+3} and Cr^{+6}). Maximum concentration in foliage was observed in winter at 13 m ($1390 \pm 76 \mu g Cr/g$), decreasing to $0.71 \pm 0.08 \mu g Cr/g$ at 1490 m. Foliage concentrations decreased as the seasons progressed. The RCW flow during the vegetation-contamination phase of the study is depicted in Fig. 9. Maximum flow during the study period was 123,000 gal/min ($4.66 \times 10^5 L/min$). Based on a chromate concentration of 20 mg/L and a measured drift fraction of 0.0003 from a representative cell (Park 1980), approximately 2 kg of hexavalent chromium was lost each day through drift. Minimum flow during the period was 46,000 gal/min ($1.7 \times 10^5 L/min$) which resulted in 0.7 kg of chromium per day. The accumulation of drift by foliage basically reflects the seasonal fluctuations in RCW flow and a characteristics growth cycle of fescue (early spring growth followed by a phase of no growth during the summer dry periods). Concentrations during a specific season most likely depicts residual drift deposition derived from a RCW flow 6 weeks earlier, following weathering by a series of precipitation events. Chromium concentrations in litter decreased rapidly with distance, ranging from a maximum of $2140 \pm 204 \mu g/g$ at 13 m during the fall to a minimum of $1.21 \pm 0.52 \mu g/g$ at 1490 m. The increase in concentrations during summer and fall periods is likely related to more exchange sites associated with increased litter biomass due to seasonal senescence of foliage.

While tabular summaries provide detailed quantitative results, graphic presentation allows the user to analyze the spatial (distance and concentration) and temporal (seasonal) aspects of the data in a more qualitative manner. A three-dimensional graphic technique was applied

Table 6
CHROMIUM CONCENTRATION IN FESCUE GRASS FOLIAGE AND LITTER SAMPLES AS A FUNCTION
OF DISTANCE FROM THE SOURCE AND SEASONALITY

Distance (m)	Chromium Concentration ($\mu\text{g/g} \pm 1 \text{ SE}$)									
	Winter (December)		Spring (April)		Summer (June)		Fall (October)		n	n
	Foliage	Litter	Foliage	Litter	Foliage	Litter	Foliage	Litter		
13	1390 \pm 76	894 \pm 171	190 \pm 28	871 \pm 86	173 \pm 15	1890 \pm 212	79.5 \pm 6.8	2140 \pm 204	9	9
65	1180 \pm 162	997 \pm 97	77.4 \pm 14.9	705 \pm 48	168 \pm 22	1380 \pm 102	37.4 \pm 5.1	1010 \pm 249	9	9
168	157 \pm 17	421 \pm 37	14.7 \pm 2.7	397 \pm 17	8.60 \pm 0.88	427 \pm 20	10.8 \pm 0.9	13.3 \pm 1.4	9	9
239	57.0 \pm 6.9	181 \pm 17	21.6 \pm 3.7	175 \pm 11	11.3 \pm 0.9	148 \pm 10	6.98 \pm 0.53	24.8 \pm 3.9	9	9
530	10.6 \pm 1.5	24.5 \pm 3.6	5.91 \pm 2.56	30.0 \pm 3.4	3.04 \pm 0.22	22.6 \pm 1.6	2.38 \pm 0.10	13.0 \pm 3.1	6	6
755	4.18 \pm 0.76	8.29 \pm 0.93	3.44 \pm 1.21	10.9 \pm 1.1	0.62 \pm 0.09	7.25 \pm 0.23	0.87 \pm 0.14	2.29 \pm 0.18	6	6
923	1.28 \pm 0.20	5.77 \pm 0.82	0.84 \pm 0.33	5.12 \pm 0.59	0.43 \pm 0.03	2.65 \pm 0.40	0.99 \pm 0.14	1.87 \pm 0.47	9	9
1172	1.20 \pm 0.36	4.00 \pm 0.51	0.45 \pm 0.25	3.64 \pm 0.21	0.17 \pm 0.02	3.85 \pm 0.45	0.92 \pm 0.14	2.24 \pm 0.57	6	6
1490	0.71 \pm 0.08	3.16 \pm 0.25	0.10 \pm 0.07	1.58 \pm 0.18	0.08 \pm 0.01	2.52 \pm 0.30	0.45 \pm 0.98	1.21 \pm 0.52	9	9

*n=6 for litter samples

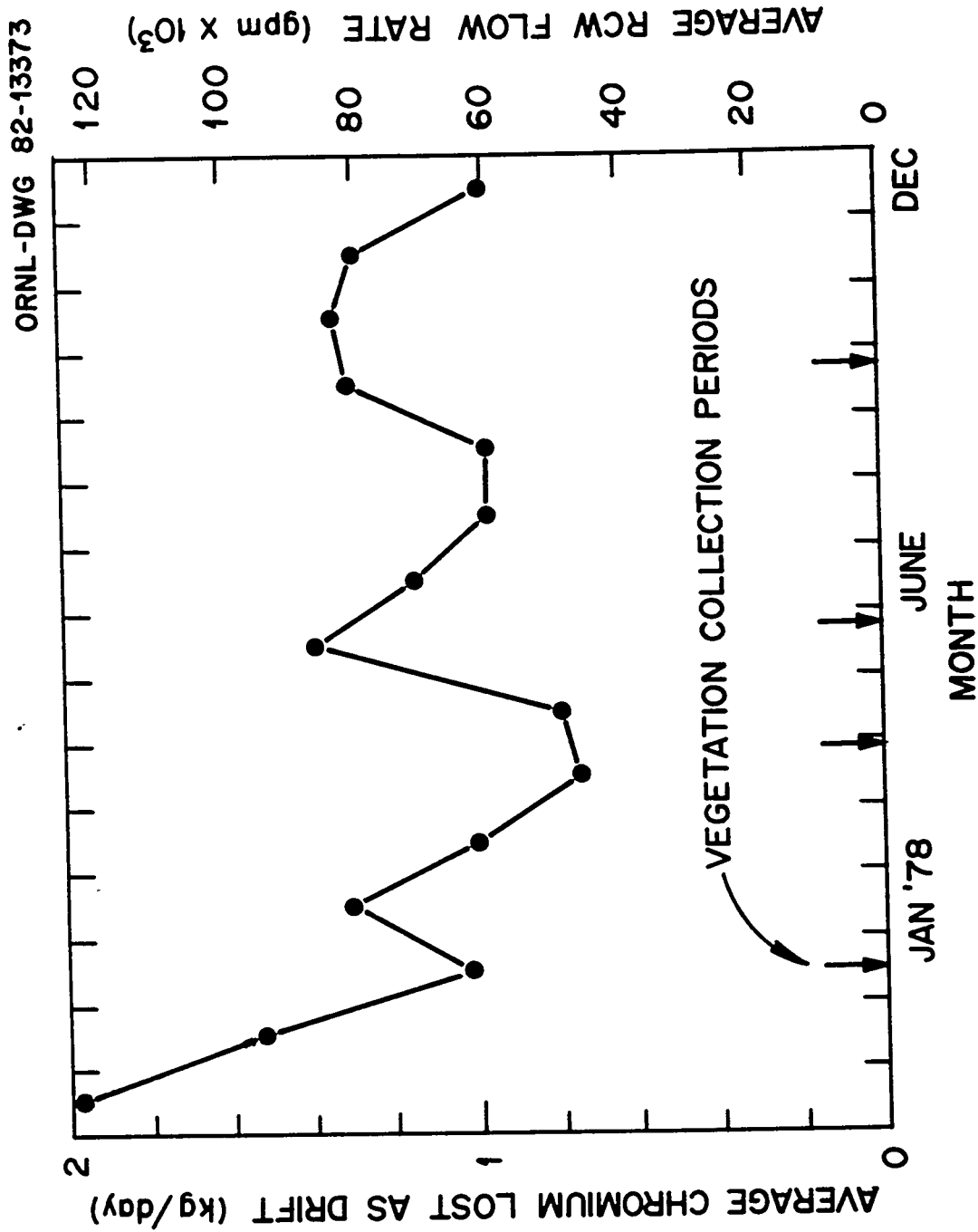


Figure 9

ESTIMATED DRIFT EMISSIONS (Kg CHROMIUM/DAY) AND RECIRCULATING COOLING WATER (RCW) FLOW RATE OF THE K-892 COOLING TOWER. CAPACITY OF COOLING TOWER IS NORMALLY EXPRESSED IN GAL/MIN (GPM) (GPM $\times 3.79 =$ L/MIN)

to the data, using the Display Integrated Software System and plotting Language-DISSPLA (ISSCO 1978). This method of display enhances extreme values and is useful for detecting trends. The concentrations in both foliage (Fig. 10A) and litter (Fig. 10B) are most evident in the first 600 m from the source, becoming insignificant at 1500 m. Concentrations in foliage peak during the winter and fall, corresponding to the two flushes of active growth and changes in RCW flow of the cooling tower. Concentrations in litter begin to increase in late summer, peaking in the fall, corresponding to the senescence of the foliage and accumulation of litter. Of particular interest are the significant increases in concentrations for both components (foliage and litter) between 250 and 300 m. This observation was originally made in 1973 and was thought to be related to a slight change in elevation at that distance (Taylor et al., 1975).

LONG TERM RETENTION AND CYCLING OF DRIFT RESIDUE

The chromium residue present on foliage represents a surface contaminant with minimal incorporation in plant tissues. In a related study approximately 24% of the deposition mass was intercepted by fescue foliage with the remainder (76%) falling directly to the soil or litter (Taylor 1983). Only 1% of the fraction intercepted was incorporated into the foliage, with the remaining fraction transferred to the soil-litter compartment by weathering, plant fragmentation or direct deposition. Approximately 5% of the chromium reaching the soil compartment is available to the plant by root uptake. The majority of the soil chromium (94%) is unavailable for incorporation into plant tissues. The cycling and retention of Cr^{+6} is illustrated in Fig. 11. The results from the several studies at ORGDP (Taylor et al., 1975, Taylor et al., 1980, and Taylor 1983) suggest that elemental pools of chromium derived from over three decades of chronic deposition do not yet pose a serious problem for the terrestrial ecosystem. This is because the long-term storage (soil-litter) accumulates as Cr^{+3} following reduction from Cr^{+6} . Trivalent chromium (Cr^{+3}) is relatively stable and biologically insignificant because of its insolubility and poor absorption by biota (NAS 1974).

SIGNIFICANCE OF CHROMATED DRIFT TO NPDES PERMIT LIMITS

In 1974 plant liquid effluents from Department of Energy (DOE) facilities were regulated to meet the National Pollutant Discharge Elimination System (NPDES) permit limit of 0.05 $\mu\text{g/mL}$ for total chromium. The potential for noncompliance to the permit limit is related to drift deposition and windage losses. Windage losses were identified as responsible for episodes of noncompliance at the DOE Paducah, Kentucky facility (Conrad 1979). Windage water deposited on the ground was transported to nearby streams through runoff. At Oak Ridge and Paducah, catchment aprons were constructed to divert the windage losses into the tower basins. Chromated water deposited in drift on vegetation or soil is likely reduced to the less soluble trivalent chromium and subsequently bound in the plant-soil system. Any

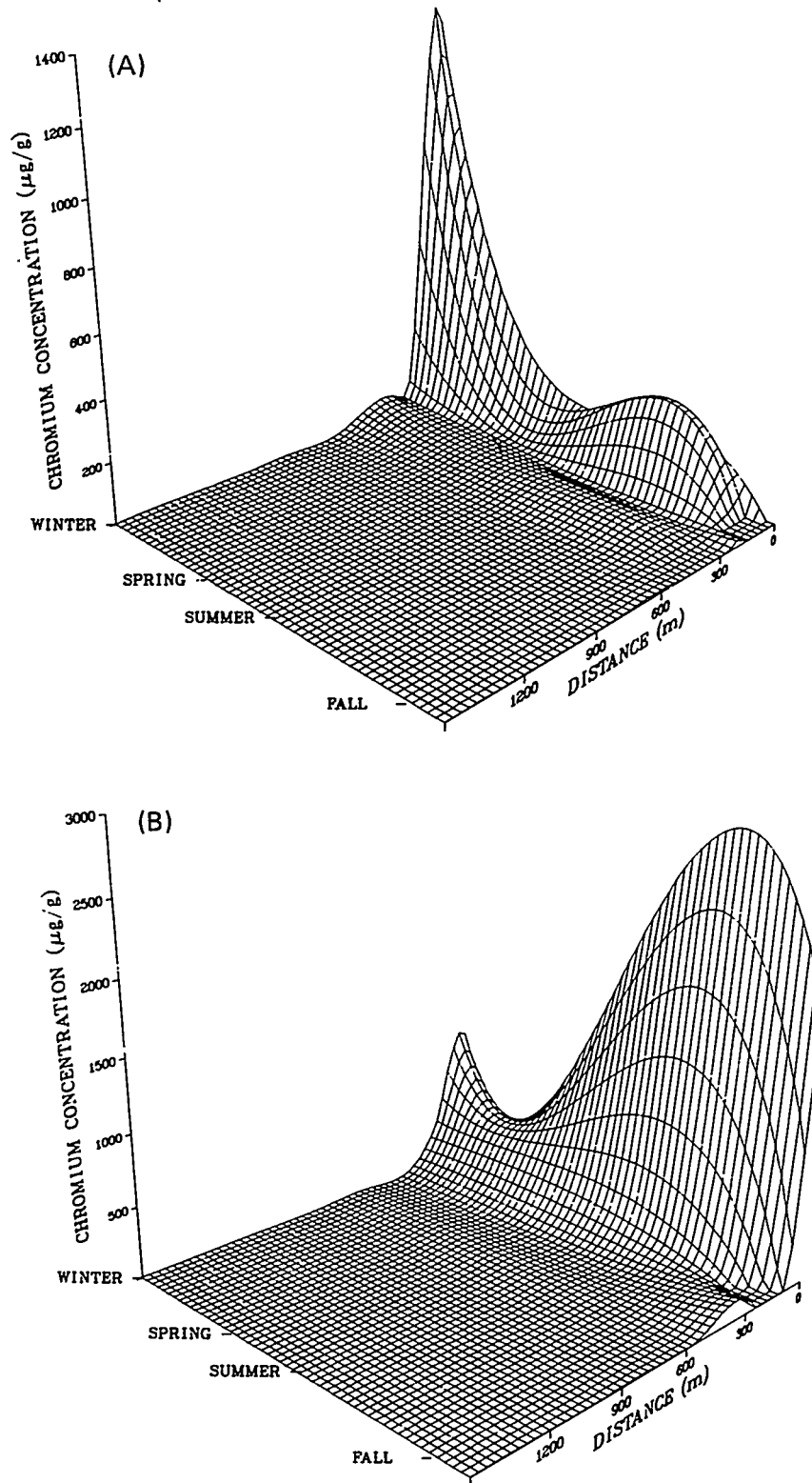


Figure 10
SEASONALITY OF CHROMIUM CONCENTRATIONS IN (A) FESCUE FOLIAGE
AND (B) LITTER ALONG A DISTANCE GRADIENT FROM THE COOLING TOWER

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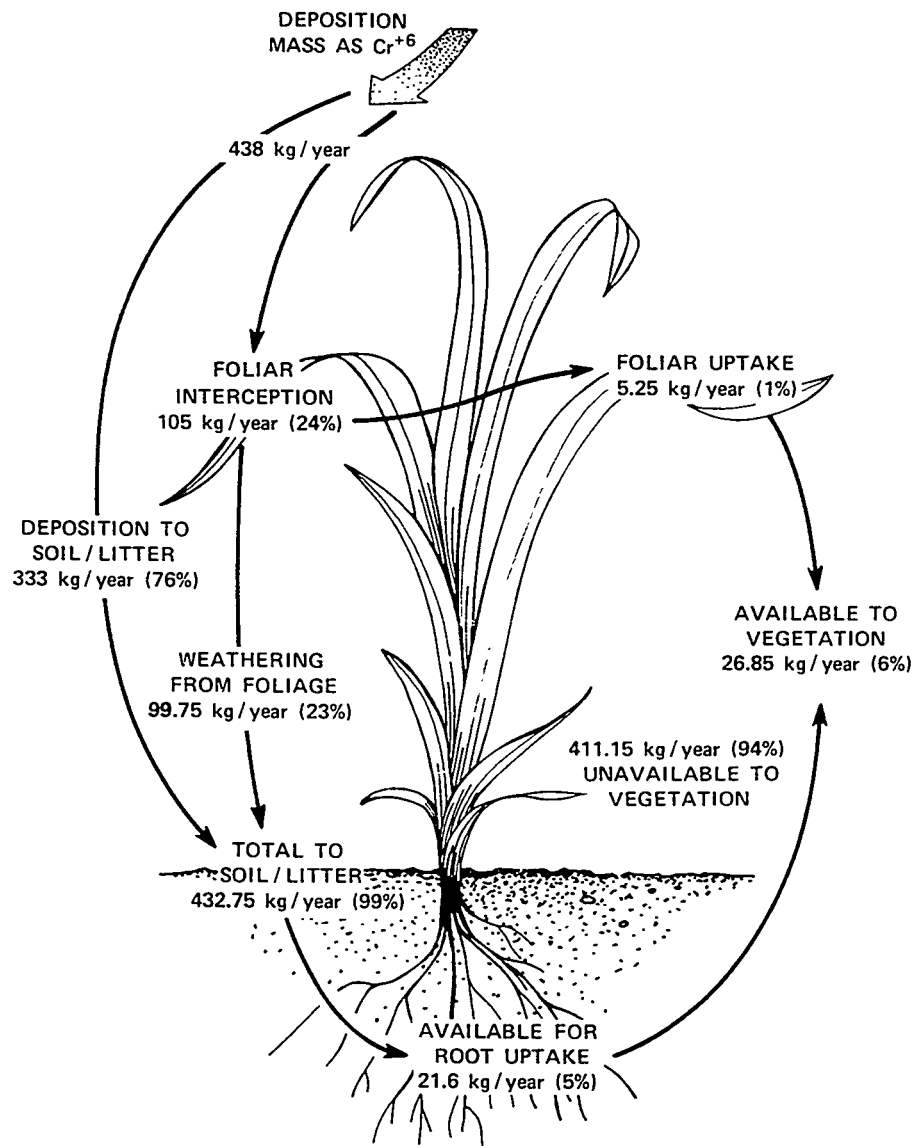


Figure 11

CYCLING OF HEXAVALENT CHROMIUM IN A FESCUE GRASS-SOIL SYSTEM

drift residue reaching the stream (Poplar Creek), either by direct deposition, weathering from plants, or in runoff, is diluted well below the NPDES permit limit and poses little potential for biological effect to aquatic systems. Episodes of noncompliance at ORGDP have not been related to drift or windage losses.

CONCLUSION

The drift rate from the ORGDP cooling towers measured in this study resulted in a drift percentage of 0.024%. This may be slightly higher than some of newer towers of similar design, but seems reasonable for the cooling towers of this age. The chromium efflux from a cell of the ORGDP towers, based on 22,740 L/min of recirculating water with a concentration of 8 ppm of chromium was 62.8 g/day. The chromium deposition analyzed with the dispersion model indicates that between 20% to 80% of chromium emitted from the tower was deposited within 1,000 m radius from the cooling tower, representing roughly 42 ha (99 acres), depending on the wind speed, and the relationship between the total deposition rate, D , and the wind speed, V , as summarized in the equation (2).

The magnitude of chromated drift and windage losses reaching the surface streams (Poplar Creek and Clinch River) is rapidly diluted below the NPDES permit limit for drinking water, and poses little risk to aquatic systems. Similarly, drift deposited as Cr^{+6} to the soil and on vegetation is reduced to the more stable Cr^{+3} . Trivalent chromium is biologically insignificant because of its unavailability to biota. Drift residue to vegetation poses little, long-term threat to the terrestrial systems (soil-plant).

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